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AN ICE THICKNESS-TENSILE STRESS RELATIONSHIP FOR LOAD-BEARING I--ETC(U)
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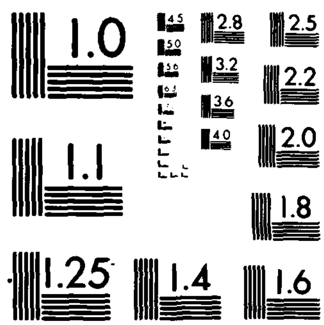

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AN ICE THICKNESS-TENSILE STRESS RELATIONSHIP FOR LOAD-BEARING ICE

Philip R. Johnson

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The "bearing capacity" of a floating ice sheet is of considerable interest. The pattern of ice thickness vs tensile stress for a fixed load and fixed ice properties was examined and showed some constant relationships. It proved possible to completely describe the ice thickness-tensile stress pattern in terms of a single number. When the load was changed by increasing the payload but not altering the geometry of the load pattern, other relationships were found that described the tensile stress in the ice sheet for any combination (over)

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of payload and ice thickness. This provides a simple method of finding tensile stress in the ice that can be used in the field. Further studies are planned.

PREFACE

This report was prepared by Philip R. Johnson, Research Civil Engineer, U.S. Army Cold Regions Research and Engineering Laboratory. The author began work in the field of ice bearing capacity while working with engineering troops building river crossings in Alaska.

The studies were funded under DA Project 4A762730AT42, Design, Construction and Operations Technology for Cold Regions, Task A, Cold Regions Military Operations, Work Unit 6, Rapid Ice Building for Engineering Use, and Work Unit 9, Expedient Snow and Ice Roads and Landing Fields.

The use of Donald Nevel's "Bearing Capacity" computer program for finding the tensile stress in an ice sheet carrying a load is gratefully acknowledged.

Donald Nevel and Austin Kovacs technically reviewed the report.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an offical endorsement or approval of the use of such commercial products.

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To obtain
Inch	25.4*	Millimeter
Pound	0.4535924	Kilogram
Ton	907.1847	Kilogram
Pound/inch^2	6894.757	Pascal
Gallon	0.003785412	Meter^3

*Exact

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INTRODUCTION

Determining the ice thickness needed to carry a given vehicle or other load has been a problem in the North. The problem is neither simple nor new, but it has become more important during the last few decades.

Several methods for solving the load-ice thickness problem have been developed but none have come into general use. Some fairly good empirical relationships have been developed, most based on a linear relationship between the square of the ice thickness and the weight of the load. Doubling the thickness of the ice will increase the load it can carry by a factor of about four. Gold (1971) discusses this relationship and Canadian practice and experience with ice crossings. Two analytical approaches have also been developed. The first, based on plate theory, predicts the deflection of an infinite floating ice sheet under a load and then evaluates the stresses in the ice as a result of the deflection. The latest and most complete presentation of this approach is by Nevel (1978). Nevel has also written several computer programs to solve individual cases using the mathematics that have been developed. Vaudrey et al. (1974) developed a finite element analysis method based on the 3-dimensional theory of elasticity as a second analytical approach.

In spite of the analyses that have been done, there is no trustworthy guidance available for use in practical field applications. The empirical relationships are not widely known and may not be able to cope with special conditions. The analytical approaches are more flexible and precise but have difficult equations and require a computer. Each solution is for a single vehicle or other load and, in the past, has not yielded relationships that can be easily generalized.

This report discusses an effort to generalize the results obtained with the analytical approach based on the thin plate studies. A computer program written by Nevel was used to solve for the maximum tensile stress in the ice due to a specific load. It was found that, when the load geometry and magnitudes and the mechanical properties of the ice are held constant, a simple curvilinear relationship exists between the maximum tensile stress and the ice thickness. These relationships form a family of curves for various loads, making it possible to simplify the relationships.

These developments make it possible to express the entire pattern of load, ice thickness and tensile stress in very simple terms. Since these relationships can be used in the field, it becomes possible to evaluate the ability of the ice to carry the proposed load easily and accurately. Emphasis is shifted from the "bearing capacity" of the ice sheet to the more proper interaction of the load and the ice sheet. The safety of the proposed loading can be evaluated in terms of the maximum tensile stress that is developed in the ice.

BEARING CAPACITY PROBLEM

General

When a load is placed on a large floating ice sheet, the ice sheet deforms and the deformation generates stresses in it. At the load the top of the ice sheet is stressed in compression while the bottom is in tension. If the load is sufficiently large, the ice sheet will begin to fail. Since ice is much weaker in tension than in compression, the bottom surface will begin to fail first; the tensile stress in the bottom of the ice sheet is therefore the controlling parameter. Nevel's "Bearing Capacity" computer program calculates tensile stress in the bottom of the ice sheet.

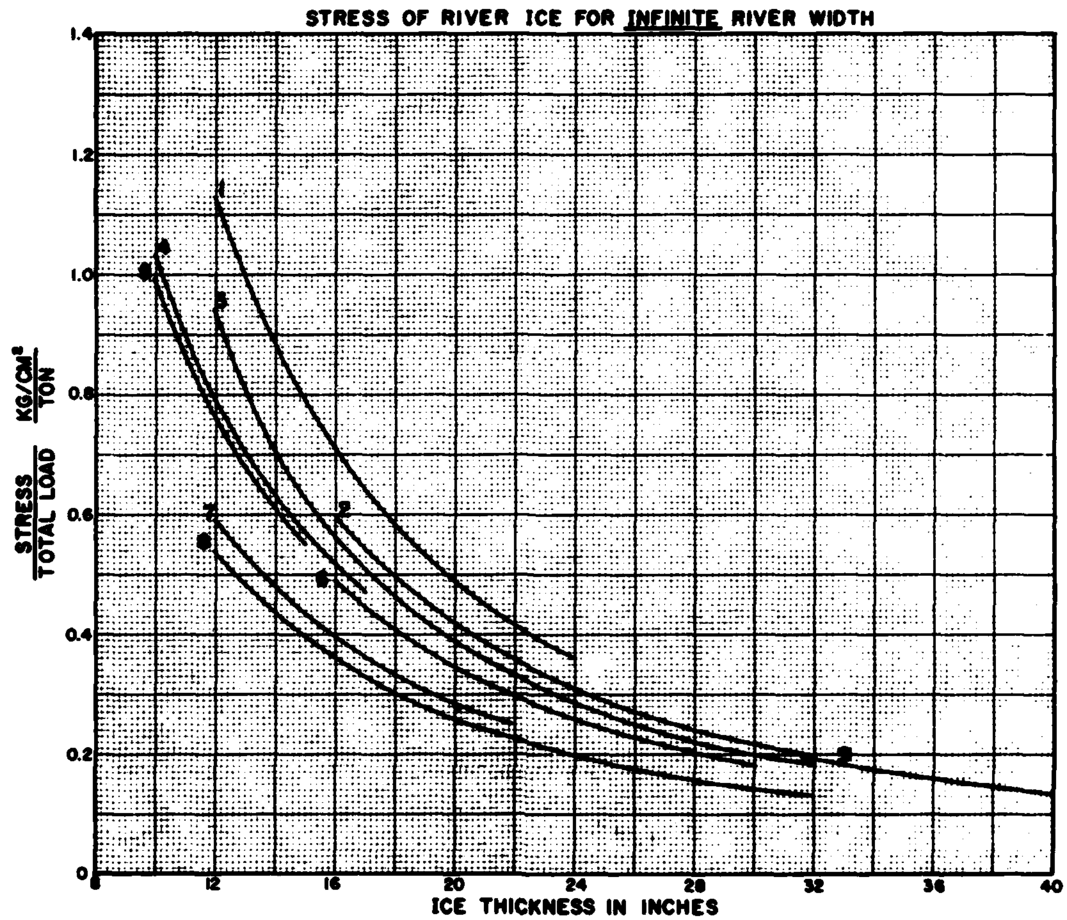
Nevel (1978) published a number of curves (his Fig. A13, reproduced here as Fig. 1) showing the load-ice thickness-tensile stress relationship for a number of vehicles. The ordinate value is tensile stress/load in $\frac{kg/cm^2}{ton}$ but, since each curve is for a constant load, identical curves can be drawn for stress (kg/cm^2 or psi) vs ice thickness. These curves form a regular family suggesting the ice thickness-tensile stress relationship can be expressed mathematically if a fitting equation can be found.

"Bearing Capacity" Program

Observing the operation of the "Bearing Capacity" program shows the means of determining critical and non-critical loads and ice stresses. The geometry and loading pattern of a selected vehicle or other load must be determined. The vehicle chosen for this study was an empty M35A2 Army cargo truck. This is the standard 2 1/2-ton 6 x 6, perhaps the most common vehicle in the Army inventory. A dash plate in the cab of the truck provided the geometric and loading information shown in Figure 2 with the exception of the wheel numbers, which were added for use in the computer analysis. An origin was selected at the center of wheel 1 (see Fig. 2) and X and Y coordinates, in inches, were found for all other wheels. The individual wheel loads for the empty truck were found and the diameter of a circle on the bottom of each tire large enough to support the wheel load, using a tire pressure of 50 psi, was calculated. Table 1 shows X, Y, load (P), and diameter of the tire support area (A) for each wheel.

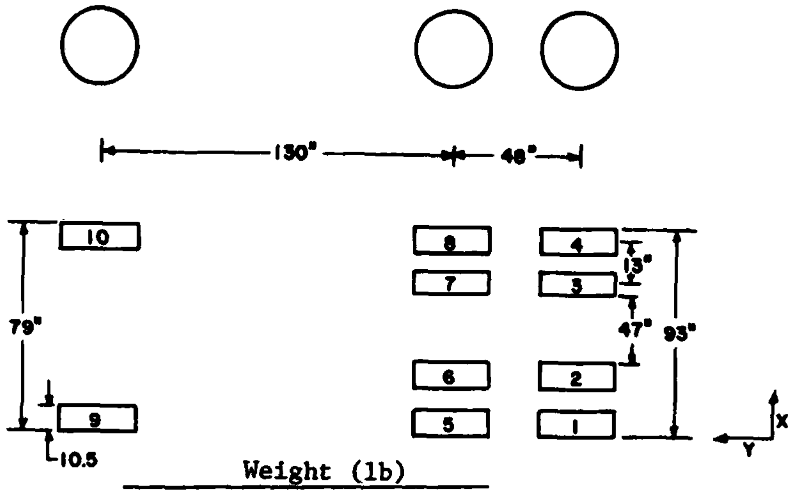
Two properties of ice required for the solution, Young's modulus and Poisson's ratio, were set at 800,000 psi and 1/3 respectively. These are commonly used values.

It was necessary to identify the "critical wheel", that with the highest tensile stress in the ice below it. Table 1 shows that the front wheels, 9 and 10, have much greater wheel loads than the rear wheels, 1-8. Tensile stresses under wheels 6 and 9 were investigated;



	Total weight (tons)
1) PCM113 or PCM577	11.5
2) MS	21.1
MS with commo van (AN/MRC-69	28.2
SP M109 how	26.2
20-ton crane	23.5
3) M51 5-ton dump truck with winch-loaded	22.0
4) M51 5-ton dump truck with winch-unloaded	11.3
5) M52 5-ton tractor with winch	9.5
6) M51 5-ton dump truck with winch-loaded and 3.5-ton bolster trailer-loaded	26.2
7) M52 5-ton tractor with winch and M172 A1 25-ton low bed semi-trailer-unloaded	16.9
8) M52 5-ton tractor with winch and M172 A1 25-ton low bed semi-trailer-unloaded	42.5
9) M48 tank	49.0

Figure 1. Load/ice thickness/tensile stress relationship for a number of military vehicles (Nevel 1978).



	Weight (lb)			Tire pressure, psi		
	Empty	X-Country	Highway	Highway	X-Country	Mud
Payload	0	5,000	10,000	50	35	15
Front Axle	6,450	6,645	6,840			
Int. Axle	3,540	5,942	8,344			
Rear Axle	3,540	5,942	8,344			

Figure 2. Dashplate data for M35A2 truck. Wheel numbers added for computer analysis.

Table 1. Computer input data, empty M35A2 truck.

Wheel	X (in.)	Y (in.)	P (lb)	A (in.)
1	0	0	885	4.7
2	13	0	885	4.7
3	70	0	885	4.7
4	83	0	885	4.7
5	0	48	885	4.7
6	13	48	885	4.7
7	70	48	885	4.7
8	83	48	885	4.7
9	7	178	3225	9.3
10	75	178	3225	9.3

the stress under wheel 9 was found to be the greater, so wheel 9 was identified as the "critical wheel." Because of symmetry, only the left-hand wheels needed to be examined. The tensile stresses under wheel 9 were found for ice thicknesses from 8 through 16 inches (see Table 2 and Figure 3).

Table 2. Tensile stress under wheel 9, empty M35A2 truck.

Ice thickness h (in.)	Tensile stress σ_t (psi)		$h\sigma_t^{.5984}$	$h\sigma_t^{.60}$
8	211.85		197.24	198.93
9	175.00		197.91	199.55
10	147.19		198.27	199.86
11	125.66		198.40	199.75
12	108.62		198.37	199.86
13	94.91		198.23	199.68
14	83.69		198.00	199.40
15	74.37		197.67	199.07
16	66.60		197.37	198.70
		Mean	197.94	199.42
		S.D.	0.43	0.43

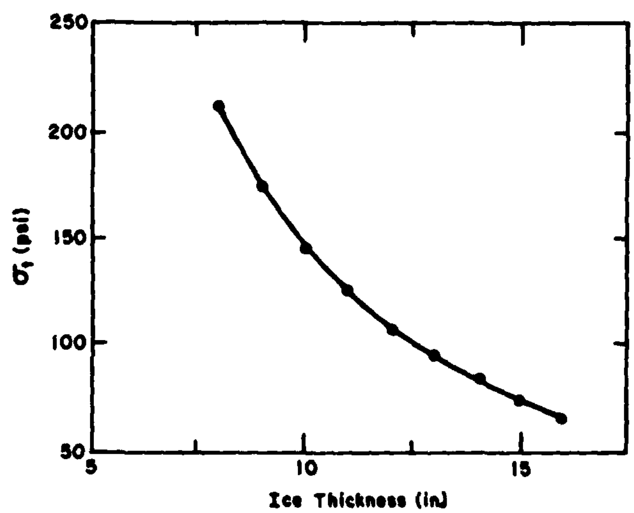


Figure 3. Tensile stress vs ice thickness for wheel 9 of empty M35A2 truck (origins suppressed).

Ice Thickness-Tensile Stress Relationship

As would be expected, the tensile stress under wheel 9 decreases as the ice thickness increases; in this respect the curve in Figure 3, where tensile stress is plotted against ice thickness, shows the same shape as those in Figure 1. Plotted on logarithmic paper in Figure 4, they show a linear relationship which can be expressed as a power curve of the form

$$\sigma_t = a\ h^b \qquad (1)$$

where σ_t is tensile stress (psi), h is ice thickness (in.), and a and b are fitted values. The solution gave least squares values of r^2 = 0.999, a = 6883.08 and b = -1.67112. However, this power curve can also be expressed in the form

$$h\ \sigma_t^{\ n} = C \qquad (2)$$

by setting n = -1/b and C = a^n. This fitting equation is

$$h\ \sigma_t^{\ .5984} = 197.94 \qquad (3)$$

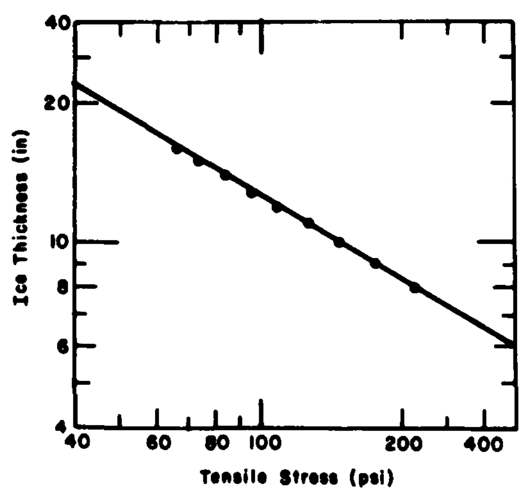


Figure 4. Logarithmic plot of ice thickness vs tensile stress.

Values of C were calculated for each set of h and σ_t. They are shown in column 3 of Table 3 and are very nearly constant. The mean value is 197.94 with a standard error of 0.43.

Important advantages are gained if a common exponent can be used to describe the ice thickness-tensile stress pattern in the ice under a load. I have found that n has always fallen near 0.60 for all vehicles investigated, so the form

$$h\ \sigma_t^{.60} = C_c \qquad (4)$$

was tested where C_c is called the Characteristic Constant when the exponent is 0.60. Changing the exponent changes the constant so values of C_c were calculated for each set of h and σ_t in Table 2. Shown in

Table 3. Axle loadings for M35A2 truck with various payloads.

Payload (lb)	0*	2500	4000	5000*	7500	10,000*
Front axle (lb)	6450	6547	6606	6645	6742	6840
Int. axle (lb)	3540	4741	5462	5942	7143	8344
Rear axle (lb)	3540	4741	5462	5942	7143	8344
Total	13,530	16,029	17,530	18,529	21,028	23,528

* From dash plate; other values by interpolation.

column 4 of Table 2, the values have a mean value of 199.42 with a standard error of 0.43. Equation 4 fits the data equally as well as eq 3.

Using a value of C_c = 200, eq 4 completely describes the ice thickness-tensile stress pattern in the ice under the "critical wheel" of the empty M35A2 cargo truck on an infinite floating ice sheet.

Variation of the Characteristic Constant with Payload

It was desired to examine the Characteristic Constant pattern of the M35A2 truck as the payload changed. A Characteristic Constant value is valid only for a single fixed geometry and fixed wheel loads. If either the geometry or the wheel loads are changed, the Characteristic Constant will change. Some regular pattern could be expected.

The M35A2 cargo truck has an empty weight of 13,530 lb and will carry a payload of 10,000 lb. Axle loadings for payloads of 0, 5000, and 10,000 lb are shown in Figure 2. Additional axle loadings for 2500, 4000, and 7500 lb were found by interpolation. All axle loads are shown in Table 3. Wheel loads were found by dividing the axle loads by the number of wheels on that axle. By developing tables of input data similar to Table 1 for each payload, the tensile stresses for selected ice thicknesses and the "critical wheel" can be found.

Wheel 9 was found to be the "critical wheel" for the empty truck but it may not remain critical as the truck is loaded. Table 3 shows the front axle load remains almost constant as the truck is loaded; the payload is carried almost entirely by the intermediate and rear axles. While the loads on the individual wheels on the intermediate and rear axles will not equal these on the front wheels, even with a full payload of 10,000 lbs the presence of many nearby loaded wheels may result in tensile stresses under those wheels exceeding those under the front wheels. Wheel 6, an indide dual on the intermediate axle, will be the most sensitive and was selected for examination. Tensile stresses under wheels 6 and 9 were found for a range of payloads and ice thicknesses. The tensile stress and ice thickness values under each wheel were converted to Characteristic Constant values using equation 4. The values obtained are shown in Table 4 and Figure 5.

Figure 5 shows the Characteristic Constant for wheel 9 is greater than that for wheel 6 until the payload reaches 3500 lb where they become equal. Beyond that payload, the Characteristic Constant of wheel 6 is higher so it becomes the "critical wheel." The Characteristic Constant of the truck is that of the highest Characteristic Constant for any wheel (see Fig. 5).

Using the vehicle Characteristic Constant shown in Figure 5 and the relationship in eq 4, the ice thickness-tensile stress pattern for the

Table 4. Characteristic constants for wheels 9 and 6 at various payloads.

	C_c	
Payload (lb)	Wheel 9	Wheel 6
0	200	181
2,500	209	204
4,000	215	219
5,000	--	228
7,500	--	250
10,000	--	270

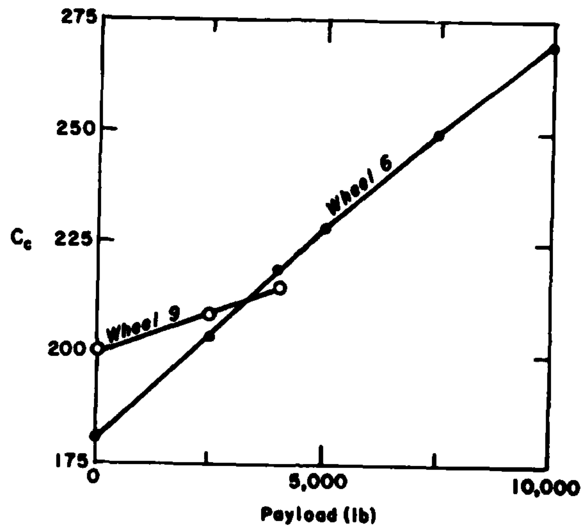


Figure 5. Characteristic constant vs payload, M35A2 truck.

vehicle can be found for any ice thickness and payload. The Characteristic Constants could have been plotted against gross weight but the payload is more convenient and useful.

Example problems

With Figure 5 and eq 4 it is now possible to solve a variety of practical problems. For convenience Table 5 was prepared to convert between σ_t and $\sigma_t^{.60}$. Three typical problems are solved below.

1. An M35A2 truck with a 7,000-lb payload is to be driven across an ice sheet. The allowable tensile stress σ_t in the ice sheet is 100 psi. Figure 5 shows that $C_c = 247$ for a 7,000-lb payload and Table 5 shows that $100^{.60} = 15.85$. The ice thickness required is $C_c/\sigma_t^{.60} = 247/15.85 = 15.6$ in.

2. A truck is carrying mail and hot food to troops engaged in winter maneuvers across a river. The total load is only 2,000 lb but the trip is important so the allowable tensile stress is 160 psi. The ice thickness required is $h = 207/21.01 = 9.9$ or 10 in.

3. ABC Logging Co. will use a surplus M35A2 truck to haul a load of fuel in 55-gal. drums to a logging site across an arm of Indianname Lake. The trail is hard and smooth so they will load the truck to its highway payload of 10,000 lb. The lake has 16 in. of good ice. What maximum tensile stress will be developed in the ice? $\sigma_t^{.60} = C_c/h = 270/16 = 16.81$. Table 5 shows the tensile stress will be about 110 psi.

Table 5. Values of $\sigma_t^{.60}$ for Values of σ_t

σ_t	$\sigma_t^{.60}$	σ_t	$\sigma_t^{.60}$
60	11.67	120	17.68
70	12.80	130	18.55
80	13.86	140	19.39
90	14.88	150	20.21
100	15.85	160	21.01
110	16.78	170	21.79

Any other similar problem can be solved as easily. The results are quite precise for good fresh water ice with mechanical properties near those assumed in the computer solutions. The limiting factor will probably be the accuracy of the measurements of ice thickness. Engineering judgement and experience are required to select allowable values of tensile stress.

CRITICAL LOADS AND ICE CONDITIONS

A tensile stress of 10 kg/cm^2 or 140 psi can be allowed for sound freshwater ice (Nevel 1978). These values allow an adequate factor of safety for short-term static or slowly moving vehicles. The allowable tensile stress should be reduced if

1. The load will be on the ice for some time.
2. A vehicle is moving faster than 10-15 mph.
3. There is a substantial amount of traffic.

Allowable tensile stresses might also be reduced in certain other cases.

These relationships have been developed for a static load on an infinite floating freshwater ice sheet. They may not apply along a shore or where there is a crack completely through an ice sheet. They do not apply to sea ice which has different and variable ice properties.

CONCLUSIONS

Means now exist for calculating the maximum tensile stress in an infinite ice sheet carrying a load of know geometry and magnitude. The technique used in this study is based on thin plate theory; a computer program written by Nevel was used to calculate tensile stress values. It

was found that the ice thickness-tensile stress relationship, when the load and ice mechanical properties are held constant, can be described by the equation

$$h \sigma_t^{.60} = C_c$$

where h is ice thickness in inches, σ_t is maximum tensile stress in the bottom of the ice sheet in psi and C_c is a constant, a numerical value related to the ice mechanical properties and the load. C_c can be found and, once it is known, this relationship completely describes the ice thickness-tensile stress pattern in the ice resulting from the load.

When the load is changed, as by increasing the payload on a truck, the value of C_c will also change in a regular manner which can be calculated. With this relationship and the above equation the tensile stress in the ice can be determined for the particular vehicle for any payload and ice thickness.

The "bearing capacity" of a floating ice sheet can now be described in terms of the maximum tensile stress in the ice, the parameter that determines whether the ice will carry the load or begin to fail. While relatively difficult equations must be solved initially, the relationships have been organized and simplified to a very simple form that is highly suited for use in the field. Figure 5, Table 5, and Equation 4 are all that is required to find the tensile stress in any large floating freshwater ice sheet carrying the truck. Only one mathematical operation is required.

This report describes the system using a single vehicle, the army M35A2 6 x 6 cargo truck. The method can be applied to any vehicle, and further studies on other vehicles are planned.

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